IMAGE FORMATION BY PASSIVE COLLECTION AND PROCESSING OF RADIO FREQUENCY SIGNALS ILLUMINATING AND SCATTERED BY CULTURAL FEATURES OF TERRESTRIAL REGION

FIELD OF THE INVENTION

The present invention relates in general to electromagnetic energy collection and processing systems, and is particularly directed to a method and apparatus for generating an image of a terrestrial region of interest, by passively collecting and processing radio waves, such as, but not limited to, those illuminating the terrestrial region from a commonly available RF emission source, for example, a commercial television transmission tower.

BACKGROUND OF THE INVENTION

Conventional schemes for generating images of objects or scenes include a variety of energy illuminating and collection methodologies, such as visible and infrared light-based processes (e.g., photography), and coherent electromagnetic radiation-based processes (e.g., synthetic aperture radar (SAR) and holography). While conventional (non-coherent) light-based photography allows image capture of exterior surfaces of objects in a scene, it does not create an image of where the light cannot go (behind the exterior surface of an object, such as into the interior of a

building or beneath a vegetation canopy, in the case of visible light).

Synthetic aperture radar and holography use coherent electromagnetic radiation (e.g., narrow bandwidth radar pulses in the case of SAR and coherent light in the case of holography) to construct an image. Advantageously, because it processes volume-based (rather than planar-based) differential phase information, holography is able to provide for the generation of a three-dimensional image of an object. Still, its use to date has been essentially limited to controlled, volume-constrained static environments, such as an opto-physics laboratory.

There are many terrestrial regions, such as cities, industrial areas, and the like, containing a wide variety of cultural features, such as buildings, bridges, towers, etc., as well as interior components thereof, for which images (including those captured at different times for determining the presence of environmental changes) are desired by a variety of information analysis enterprises. Curiously, many if not most of such terrestrial regions are continuously illuminated by a relatively powerful narrowband radio frequency (RF) transmitter, such as television broadcast towers, creating a condition known as 'RF daylight'. Because of the partial transparency to such RF emissions (especially at and below VHF and UHF frequencies) of many objects, including both natural

vegetation and man-made structures, these RF-daylight signals can be expected to be reflected/scattered off cultural features (including both exterior and interior surfaces) of an illuminated region.

SUMMARY OF THE INVENTION

In accordance with the present invention, advantage is taken of this 'RF daylight' phenomenon, to passively acquire RF reflectance or scattering coefficient parameter values of multiple points within a prescribed three-dimensional volume being illuminated by an RF transmitter. As will be described, the passive image generation system of the invention collects and processes RF energy that may be reflected - scattered from multiple points of a three-dimensional space within a region being illuminated by a coherent RF energy source, such as a television transmitter.

Pursuant to a non-limiting embodiment, the system of the invention employs a front end, RF energy collection section that contains a reference signal collector (antenna) which collects non-scattered RF energy emitted by an RF reference source illuminating the potentially cultural feature-containing terrestrial region of interest. A second, dynamic scattered image energy collector mounted on a platform, overflying the illuminated terrestrial region collects RF energy that

has been scattered - reflected from various points of cultural features (such as buildings and contents thereof) within a three-dimensional volume of space containing the terrestrial region.

The reference signal collector and the scattered image energy collectors may comprise airborne or spaceborne RF energy collection platforms. Alternatively, reference signal collection and scattered energy collection may involve the use of a common RF energy collector, or respectively separate energy collectors located on the same platform. Also, the image energy collector may be located on an airborne or spaceborne platform and the reference signal collector may comprise a ground-based receiver. The scattered RF image energy collection platforms containing the scattered energy collector(s) are dynamic in plural non-coincident travel paths, to ensure that energy collected from the terrestrial region of interest will be derived by way of multiple offset views of that region, which provides the resulting aperiodic lattice additional power to resolve image ambiguities and enhance the three-dimensional imaging capability of the invention. Once captured by their respective energy receiver sections, the RF reference signal energy and the RF image energy are digitized and stored, so that they may be readily coupled to an image processing section.

The scattered image data processing section assumes that the source of RF energy illuminating the three-dimensional spatial volume of interest is located at some fixed location in space, known a priori. A respective location of a scattered RF energy collector moving along a respective travel path above and past the terrestrial region is defined by a set of collection aperture coordinates. Where the scattered RF energy collector is used to simultaneously collect non-scattered energy emitted from the reference signal source, termed a 'self-referential' embodiment, the received signal y(t) produced by the RF energy collector contains the direct path signal from the illumination source to the collector plus time-delayed, Lorentz-transformed RF energy that may be scattered or reflected from the illuminated location and incident upon the collection aperture.

Because the coordinates of the source of the reference signal are spatially displaced from the location of a respective illuminated point, there will be a time delay associated with the reference signal's travel path from the source to the potential scattering location, and also and a time delay associated with the reference signal's travel time from the reference signal source to the RF energy collection aperture. In addition, there is a time delay associated with the travel time of the RF energy scattered from the illuminated location to

the scattered image energy collector.

To properly correlate the reference signal emanating from the illuminating source with the RF energy signal received by the moving collector, it is necessary to account for these delays, as well as the time-scaling of the signal received by the energy collector resulting from the fact its platform is moving relative to the illuminated potentially scattering location. To this end, the signal received at the dynamic collector is applied to a first Lorentz transform operator that accounts for signal propagation delay and performs a Lorentz transform of the signal from its moving frame of reference at the collection aperture location to the static frame of reference of the illuminated point in space. The output of this first Lorentz transform operator is then applied to a delay which imparts a delay associated with the reference signal's propagation time from the source to the illuminated location. The combined effect of this first Lorentz transform and delay operation serves to transform the reference signal component of the energy received at the collection aperture to the illuminated location. The transformed signal is coupled as a first input of a correlation multiplier.

The received signal is further applied to a second Lorentz transform operator which accounts for signal propagation delay and performs a second Lorentz transform

of the received signal from its moving frame of reference to the static frame of reference of the illuminated point in space. Because the 'self referential' embodiment of the invention provides for the collection of the scattered energy and reference illumination signals by a common energy collector, the received signal at the dynamic collection aperture also contains the reference illumination signal. In order remove this reference signal component from the desired scattered image component, the output of the second Lorentz transform operator is coupled to a reference signal suppression operator, that serves to significantly null out the reference signal component. The resultant reference-nulled signal represents the scattered component of the receive signal as transformed to the illuminated location and is coupled as a second input of the correlation multiplier.

Where the scattered energy signal and the reference signal are collected by separate energy collectors, the signal received by the scattered energy collection aperture will not contain a potentially dominant reference signal component that requires removal, as described above. In this instance, the received signal is applied only to a single Lorentz transform operator the output of which is coupled to the correlation multiplier. Moreover, where a copy of the reference signal is

available, no Lorentz transform of the illuminating reference signal is necessary; instead, the reference signal need only be compensated for the signal propagation time delay and coupled to the correlation multiplier.

The correlation multiplier multiplies the reference signal transform component by the scattered signal transform component to produce a product that is integrated over a relatively long integration interval, such as one on the order of several tens of seconds to several tens of minutes, and sufficient to ensure that only scattered energy values associated with RF frequency from the reference source illuminating the scattered location will constructively combine, whereas all others will destructively cancel. This produces a scattering coefficient for the illuminated location that is representative of reference signal energy from the transmission reference signal source as scattered by that location.

The scattering coefficient information is a complex interference pattern (containing both amplitude and phase components) containing all the information necessary to recreate a three-dimensional monochromatic image of the illuminated scene. Namely, the coherent complex correlation provides scene information content that is only a function of scene scattering and collector

geometry. Assuming that the scene does not change substantially over the collection period, the synthetic aperture amplitude and phase distribution may be collected and extracted sequentially rather than simultaneously.

The output of the correlation integrator may be coupled to a downstream image utility subsystem, such as a virtual reality simulator, multi-image slice display device, and the like, for generation of the three-dimensional image of the scene, and facilitate stereoscopic viewing of the image. The resolution to which the illuminated scene may be imaged (three-dimensionally) is limited by the Rayleigh wavelength (i.e., one-half the wavelength) of the illuminating reference source.

BRIEF DESCRIPTION OF THE DRAWINGS

Figure 1 diagrammatically illustrates an embodiment of a passive image generation system of the invention;

Figure 2 diagrammatically illustrates a scattered RF image energy collector coupled with a platform overflying an illuminated region by way of a plurality of respectively different, non-parallel 'fly-by' paths;

Figure 3 diagrammatically illustrates the overall mechanism carried out by the image processing section of Figure 1;

Figure 4 is a correlation signal processing diagram associated with the operation of the RF energy processing section of Figure 1;

Figure 5 shows an example of a reference signal suppression operator;

Figure 6 shows a reduced complexity correlation signal processing diagram; and

Figure 7 shows a reduced complexity implementation of the correlation signal processing diagram of Figure 4, where the differential Lorentz transform operators are replaced by a Doppler shift mechanism.

DETAILED DESCRIPTION

Before describing in detail the new and improved passive image generation scheme of the present invention, it should be observed that the scattered RF collection and processing system of the invention resides primarily in a prescribed arrangement of conventional radio wave collection subsystems and components, and associated digital processing equipment that processes digital data representative of scattered RF energy received by the radio wave collection subsystems, in order to derive pixel/voxel data representative of cultural features of a region illuminated by the RF energy illuminating a particular scene of interest.

Consequently, the configuration of the image

generation system of the invention has, for the most part, been illustrated in the drawings by readily understandable block diagrams, which show only those specific details that are pertinent to the present invention, so as not to obscure the disclosure with details which will be readily apparent to those skilled in the art having the benefit of the description herein. Namely, the diagrammatic illustrations to be described are primarily intended to show the major components of the invention in a convenient functional grouping, whereby the present invention may be more readily understood.

As pointed out briefly above, the passive image generation system of the present invention is operative to collect and process RF energy that may be reflected - scattered from multiple points of some prescribed portion of a three-dimensional space being illuminated by an RF energy source, such as a commercial television transmitter, as a non-limiting example, that is typically situated in proximity to a terrestrial region that can be expected to contain cultural features (e.g., buildings and contents thereof) of which an image is desired. For this purpose, as diagrammatically illustrated in Figure 1, the image generation system of the invention includes a front end, RF energy collection section 10, and a downstream RF energy processing section 20.

In the system diagram of Figure 1, the RF energy collection section 10 is shown as containing a first, reference signal collector 11, that is operative to collect non-scattered RF energy 12 emitted by an RF source 13, such as a commercial television broadcast tower, that illuminates the potentially cultural feature-containing terrestrial region of interest. The RF energy collection section also includes a second, scattered image energy collector 14, that is operative to collect RF energy that has been scattered - reflected from various points of cultural features (such as buildings and contents thereof) 15 within a three-dimensional volume of space 16 containing the terrestrial region of interest being illuminated by the source 13.

As non-limiting examples, each of the reference signal collector 11 and the scattered image energy collector 14 may comprise respective (airborne or spaceborne) RF energy collection platforms, containing their own antenna and receiver subsystems. In an alternative configuration, both the reference signal collector and the scattered or image energy collector may involve the use of a common RF energy collector, or respectively separate energy collectors located on the same platform. As a further variation, the image energy collector 14 may be located on an airborne or spaceborne platform and the reference signal collector may comprise

a ground-based receiver, as shown at 17.

Regardless of the energy collection arrangement employed, the one or more scattered RF image energy collection platforms containing the scattered energy collector(s) are dynamic in plural non-coincident travel paths, to ensure that energy collected from the terrestrial region of interest will be derived by way of multiple offset views of that region. That is, as shown in Figure 2, the scattered RF image energy collector 14 (which may include more than one image energy collector) is coupled with a platform one which overflies the illuminated region 16 by way of a plurality of respectively different, non-parallel 'fly-by' paths (three of which are shown at 31, 32 and 33, as non-limiting examples), so as to provide for the gathering of three-dimensionally scattered RF energy from cultural features in the illuminated region.

Namely, the synthetic aperture realized by the collector geometry is three-dimensional, since the travel path of the collector over the illuminated region of interest effectively follows a curved path and is not likely to be at exactly the same altitude on each pass. This provides the resulting aperiodic lattice additional power to resolve image ambiguities and enhances the three-dimensional imaging capability of the invention.

It may also be noted that the gathering of scattered

energy may be carried out by multiple RF energy collection platforms traveling simultaneously or sequentially along different paths, or by a single platform sequentially traveling (and potentially repeatedly) along different paths. Once captured by their respective energy receiver sections, the RF reference signal energy and the RF image energy are digitized and stored, so that they may be readily coupled to the image processing section 20.

As non-limiting examples, the coupling the stored RF energy captured and stored on board the dynamic airborne or spaceborne platform to the image processing station may be accomplished directly by providing the image processing section 20 on the same platform as the energy collector, such as on board an aircraft or spacecraft; it may also be accomplished by landing the platform and transferring the stored data to a terrestrially located image processing section; and it may be communication channel-downlinked (as shown by broken links 21 and 22 in Figure 2) to the image processing station.

Figure 3 diagrammatically illustrates the overall mechanism that is carried out by the image processing section for processing RF energy data that has been collected by the front end section, so as to obtain a set of (spatially orthogonal scattering coefficient values) for the case of an arbitrary, illuminated location (pixel

point p_i), defined by a respective set of (three-dimensional) cartesian coordinates (x_i, y_i, z_i) within the volume of space 16 of the terrestrial region illuminated by the reference source 13. In terms of the diagrammatic illustration of Figure 1, described above, the source 13 of RF energy illuminating the three-dimensional spatial volume of region 16 is denoted as a reference signal source $s_o(t)$, which is assumed to be located at some fixed location in space, having coordinates (x_0, y_0, z_0), known a priori.

A respective location of a scattered RF energy collector 14 (as it moves along a respective travel path 30 above and past the terrestrial region 16) is defined by a set of collection aperture (a) coordinates (x_a, y_a, z_a), which may be readily provided by precision navigation instrumentation, such as a GPS-based position location subsystem. In the embodiment illustrated by the spatial diagram of Figure 3, the scattered RF energy collector 14 is also used to simultaneously collect non-scattered energy emitted from the reference signal source $s_o(t)$, so as to provide what is termed as a 'self-referential' approach. Namely, a received signal $y(t)$ produced by the RF energy collector 14 contains the direct path signal $s_o(t)$ from the source 13 to the collector 14, as well as time-delayed, Lorentz-transformed RF energy that may be scattered or reflected from the illuminated location p_i,

and incident upon the collection aperture (a) of the collector 14.

Advantages of this self-referential embodiment include the ability to use a single energy collection location to acquire all required waveforms, the elimination of errors, such as time transfer, local oscillator offset, processing signals that have propagated through different media, and open loop differential time delay, as well as the use of less complex processing (differential Lorentz transform) and the elimination of the requirement for an absolute illumination signal reference. A disadvantage is the increase in cross-correlation noise, which requires the use of an illumination source signal suppression operator, as will be described.

The signal Y(t) may be represented in equation (1) as:

$$y(t) = (g_{oa}/r_{oa}) * s_o(\gamma_{oa}[t-(r_{oa}/c)] +$$

$$\sum_i (g_{oia}\sigma_i^{1/2}/r_{oi}r_{ia})\, s_o(\gamma_{ia}[t-(r_{oi}+r_{ia})/c]) \quad (1)$$

where the first term corresponds to the direct path signal from the source $s_o(t)$, and the second, summation term corresponds to the scattered signal from the illuminated location p_i. The components of equation (1) may be defined as follows:

c = the speed of light;

t = time as measured in the moving collection aperture (a) frame of the collector 14;

g_{oa} = the gain power factor for the path from the source 13 to the aperture of the moving collector 14;

g_{oia} = gain power factor for the path from the source 13 to the ith scatterer at illuminated location p_i to the collection aperture of the collector 14;

r_{oa} = the distance from the source 13 to the collection aperture of the collector 14;

r_{oi} = the distance from the source 13 to the ith scatterer;

r_{ia} = the distance from the ith scatterer at illuminated location p_i to the collection aperture of the collector 14;

γ_{oa} = Lorentz time scaling for the path from the source 13 to the collection aperture of the collector 14;

γ_{ia} = Lorentz time scaling for the path from the potential scatterer location p_i to the collection aperture of the collector 14; and

σ_i = the scattering coefficient for the ith scatterer at illuminated location p_i.

The Lorentz time scaling γ_{oa} may be defined as:

$$\gamma_{oa} = (1 - r_{oa}/c)/(1 - (r_{oa}/c)^2)^{1/2} \quad (2).$$

The Lorentz time scaling γ_{ia} may be defined as:

$$\gamma_{ia} = (1 - r_{ia}/c)/(1 - (r_{ia}/c)^2)^{1/2} \quad (3).$$

The gain power factor g_{oa} may be expressed as:

$$|g_{oa}|^2 = \lambda^2 G_t(\hat{a}_{oa}) G_r(\hat{a}_{oa}) / 16\pi^2, \quad (4)$$

and the gain power factor g_{oia} may be expressed as:

$$|g_{oia}|^2 = \lambda^2 G_t(\hat{a}_{oi}) G_r(\hat{a}_{ia}) / 64\pi^3, \quad (5)$$

where

G_t, G_r are respective gains of the transmitting antenna of the illuminating source 13 and the receiver antenna(s) of the collector 14,

the values $\hat{a}$ are path unit vectors, and

λ is the wavelength of the RF signal transmitted by the illuminating source 13.

It should be noted that, due to the differential processing mechanism of the invention, the coordinates (x_0, y_0, z_0) used to specify the location of the reference signal source $s_o(t)$ need not specify the exact location of the transmitter 13. As long as the coordinates (x_0, y_0, z_0) are reasonably proximate to the actual location of the reference signal source $s_o(t)$, the processed result for the illuminated location p_i (and all others) will be spatially shifted from the image produced if the coordinates of the source 13 were known with precision; as a consequence, the generated scene will simply be a spatially shifted image, containing the same resolvable cultural details that would be obtained were the exact location of the phase center of the transmitter's emitted RF signal known a priori.

Because the coordinates (x_0, y_0, z_0) of the source of the reference signal $s_o(t)$ are spatially displaced from the location (x_i, y_i, z_i) of the illuminated point p_i of interest, there will be a time delay shown by broken lines τ_{oi} associated with the reference signal's travel path from the source $s_o(t)$ to the potential scattering location p_i, and a time delay shown by broken lines τ_{oa} associated with the reference signal's travel time from the reference signal source $s_o(t)$ to the RF energy collection aperture at coordinates (x_a, y_a, z_a). In addition, broken lines τ_{ia} represent the time delay associated with the travel time of the RF energy scattered from the illuminated location p_i to the received image signal coordinates (x_a, y_a, z_a) of the scattered image energy collector 14.

In order to properly correlate the reference source signal $s_o(t)$ emanating from the source 13 with the RF energy signal $y(t)$ received by the moving collector 14, it is necessary to account for these delays, as well as the time-scaling of the signal received by the energy collector 14 resulting from the fact its platform is moving relative to the illuminated location p_i. These adjustments are shown in the correlation signal processing diagram of Figure 4.

In particular, the received signal $y(t)$ as collected by the collector 14 at the RF energy collection aperture

coordinates (x_a, y_a, z_a) is applied to a first processing path that includes a first Lorentz transform operator 41. This first Lorentz transform operator accounts for the delay τ_{oa} and performs the first Lorentz transform γ_{oa} of the signal y(t) from its moving frame of reference at collection aperture location (x_a, y_a, z_a) to the static frame of reference of illuminated location p_i.

The output of the first Lorentz transform operator 41 is then applied to a delay 43, which imparts a delay τ_{oi} associated with the reference signal's travel time from the source $s_o(t)$ to the illuminated location p_i. The combined effect of this first Lorentz transform and delay operation serves to transform the reference signal component of the energy received by the collector 14 to the location p_i. The output of delay 43 is coupled as a first input 42 of a correlation multiplier 44.

The received signal y(t) is further applied to a second processing path that includes a second Lorentz transform operator 45, which accounts for the delay τ_{ia} and performs a second Lorentz transform γ_{ia} of the received signal y(t) from its moving frame of reference at location (x_a, y_a, z_a) to the static frame of reference of location p_i. Because the 'self referential' system of Figure 3 provides for the collection of both the scattered energy and reference illumination signals by means of a common energy collector 14, the received

signal $y(t)$ also contains the reference illumination signal $s_o(t)$ (which can be expected to be a substantial or dominant portion of the received signal).

In order remove this reference signal component $s_o(t)$ from the desired scattered image component of the received signal $y(t)$, the output of the second Lorentz transform γ_{ia} operator 45 is coupled to a reference signal suppression or 'correlation discriminant' operator 47, that serves to significantly null out (e.g., reduce on the order of 30-60 dB or more) the amplitude of the reference signal component. As a non-limiting example, the reference signal suppression operator 47 may comprise a spectral inversion-based nulling mechanism of the type diagrammatically illustrated in Figure 5.

As shown therein, the received signal $y(t)$ is coupled as an input to a phase locked loop tracking operator 51, which produces an output representative of $\cos(2\gamma_o\omega_o t)$. This frequency shifted signal is then multiplied in a multiplier 53 by the signal $y(t)$, to produce a spectral inversion of the received signal, that places the desired information signal (containing the scattered information) at a sideband of the illuminating reference. This spectrally inverted version of the received signal is then differentially combined with the received signal $y(t)$ in differential combiner 55, which excises or nulls out the spectrally coincident reference

component in the two multiplied signals, leaving only the desired scattered energy component. The resultant reference-nulled signal output by the reference signal suppression operator 47, which represents the scattered component of the receive signal y(t) as transformed to the illuminated location p_i, is coupled as a second input 46 of the correlation multiplier 44.

Where the scattered energy signal and the reference signal are collected by separate energy collectors, the signal y(t) provided by the energy collector 14 will not contain a potentially dominant reference signal component that requires removal, as described above. In this instance, as shown in Figure 6, the signal y(t) is applied only to the Lorentz transform operator 45, the output of which is coupled to the second input 46 of multiplier 44. Also, where a copy of the reference signal $s_o(t)$ at illumination source location (x_0, y_0, z_0) is available, no Lorentz transform of the illuminating reference signal is necessary; instead, the reference signal need only be coupled through a delay 43 to compensate for the travel time delay τ_{oi}, with the output of delay 43 being coupled to the first input 42 of the multiplier 44 as described above.

As shown in Figures 4 and 6, the multiplier 44 multiplies the reference signal transform γ_{oa} based component at its input 42 by the scattered signal

transform γ_{ia} based component at its input 46, so as to produce a product that is summed or integrated by a correlation integrator 48. The integration period of integrator 48 is of a relatively long duration (which may be on the order of several tens of seconds to several tens of minutes, as a non-limiting example), that is sufficient to ensure that only scattered energy values associated with RF frequency from the source $s_o(t)$ illuminating the location p_i will constructively combine, whereas all others will destructively cancel, leaving as a valid scattering coefficient information c_i for illuminated location p_i only that derived from reference signal energy emanating from the transmission reference signal source 13.

The scattering coefficient information obtained from the above described correlation processing is a complex interference pattern (containing both amplitude and phase components) containing all the information necessary to recreate a three-dimensional monochromatic image of the illuminated scene. Namely, the coherent complex correlation provides scene information content that is only a function of scene scattering and collector geometry. Assuming that the scene does not change substantially over the collection period (which may involve multiple passes of the image collecting platform(s)), it does not matter that the synthetic

aperture amplitude and phase distribution is collected and extracted sequentially rather than simultaneously).

The output of the integrator 48 may be coupled to a downstream image utility subsystem 49, such as but not limited to a virtual reality simulator, multi-image slice display device, and the like, for generation of the three-dimensional image of the scene, and facilitate stereoscopic viewing of the image at any perspective (within scene illumination and collection limits).

The resolution to which the illuminated scene may be imaged is limited by the Rayleigh wavelength (i.e., one-half the wavelength) of the illuminating reference source $s_o(t)$. As a non-limiting example, for an illuminating frequency on the order of 50 MHz, the image feature resolution may be on the order of ten feet, while for an illuminating frequency on the order of 500 MHz, the image feature resolution may be on the order of one foot.

Figure 7 shows a reduced complexity implementation of the correlation signal processing diagram of Figure 4, where the differential Lorentz transform operators are replaced by a Doppler shift mechanism. In this case the Lorentz transform operator 41 is removed and the Lorentz transform operator 45 is replaced by a multiplier 45M, to which the signal $y(t)$ and the signal $e^{j\omega(t)}$ are applied, where $\omega(t)$ = Lorentz $(\gamma_{oa}-\gamma_{ia})$.

With respect to sensitivity of the image collection

subsystem, it may be noted that the collection bandwidth should be sufficient to encompass the RF illumination source (making maximum use of its power); however, the ultimate bandwidth of the synthetic aperture (hologram) formation process is objectively zero. The correlation operation obtains a Doppler spread of the scene's cultural features as seen by the collector, and is usually much smaller the transmitted signal's bandwidth. As a non-limiting example, the Doppler spread might typically be tens of kHz at UHF, so that nearly 30 dB sensitivity improvement is immediately realized upon correlation when a television transmitter is employed as the illuminating signal source. From a functional standpoint (assuming that other system-level factors do not limit integration time), the total observation time will establish a lower bandwidth, which may be on the order of milli- or even micro-Hz. As a result, processing gain on the order of 90 dB or greater may be achieved, allowing the imaging of relatively weakly illuminated scene features, using practical implementation G/T collector components.

It may also be noted that the correlation process described above allows indefinite reduction of co-channel interference and noise biases, as such waveforms are not coherent with the transmitted signal. In addition, correlation quality improves directly with the number of

samples, due to the presence of a high signal to noise plus interference reference signal, even though scattered signals received from scene features may be well below the ambient noise plus co-channel interference level. A practical implication involves imaging scene illumination points that are relatively close to the reference source relatively quickly - using a relatively low G/T collector, while scene elements at the edge of the observed region may require the coherent summation of many passes of the collector.

Because the potential collecting volume of the synthetic aperture is quite immense (e.g., tens or hundreds of miles in effective diameter), even relatively dimly illuminated regions of the scene having high co-channel interference can be imaged. The rate at which the synthetic aperture can be filled with scattered image data is proportional to the collector's G/T, which implies a trade-off between collector G/T versus the time required to form a given quality image.

As will be appreciated from the foregoing description, the passive imaging system of the present invention takes advantage of RF daylight created by commonplace RF illumination sources, such as a television broadcast tower, to passively acquire RF scattering coefficients for multiple points within a prescribed three-dimensional volume being illuminated by the RF

transmitter. The scattering coefficients provide a complex interference pattern having amplitude and phase components and containing all the information necessary to recreate a three-dimensional monochromatic image of the illuminated scene. Thus, the coherent complex correlation provides scene information content that is only a function of scene scattering and collector geometry. The scene information may be coupled to an image utility subsystem, such as a virtual reality simulator, multi-image slice display device, and the like, for generation of the three-dimensional image of the scene, and facilitate stereoscopic viewing of the image.

While we have shown and described several embodiments in accordance with the present invention, it is to be understood that the same is not limited thereto but is susceptible to numerous changes and modifications as known to a person skilled in the art, and we therefore do not wish to be limited to the details shown and described herein, but intend to cover all such changes and modifications as are obvious to one of ordinary skill in the art.